

Near-barrier Fusion Induced by Stable Weakly Bound and Exotic Halo Light Nuclei

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Abstract. The effect of breakup is investigated for the medium weight ${}^6\text{Li}+{}^{59}\text{Co}$ system in the vicinity of the Coulomb barrier. The strong coupling of breakup/transfer channels to fusion is discussed within a comparison of predictions of the Continuum Discretized Coupled-Channels model which is also applied to ${}^6\text{He}+{}^{59}\text{Co}$ a reaction induced by the borromean halo nucleus ${}^6\text{He}$.

INTRODUCTION

In reactions with weakly bound nuclei, the influence on the fusion process of coupling both to collective degrees of freedom and to breakup/transfer channels is a key point for the understanding of N-body systems in quantum dynamics. The diffuse cloud of neutrons of halo nuclei was expected to lead to significant enhancement of the fusion cross section at sub-barrier energies as compared to predictions of one-dimensional barrier penetration models [1]. This was understood in terms of the dynamical processes arising from strong couplings to collective inelastic excitations of the target and projectile [1, 2]. However, in the case of reactions where at least one of the colliding nuclei has a sufficiently low binding energy for breakup to become a competitive process, conflicting model predictions and experimental results were reported [1, 2]. Recent experimental results with ${}^{6,8}\text{He}$ beams show that the halo of ${}^6\text{He}$ does not enhance the fusion probability, confirming the prominent role of neutron transfer in ${}^6\text{He}$ induced fusion reactions [1, 3, 4, 5]. The effect of non-conventional transfer/stripping processes appears to be less significant for stable weakly bound projectiles [6, 7] on medium-mass target as compared to ${}^{208}\text{Pb}$ [8].

Excitation functions for sub- and near-barrier total (complete + incomplete) fusion cross sections measured for the ${}^{6,7}\text{Li}+{}^{59}\text{Co}$ reactions [6] were compared to Continuum-Discretized Coupled-Channels (CDCC) calculations [9] indicating only a small enhancement of total fusion for the more weakly bound ${}^6\text{Li}$ below the Coulomb barrier, with similar cross sections for both reactions at and above the barrier [10]. This result is consistent with the rather low breakup cross sections measured for the ${}^6\text{Li}+{}^{59}\text{Co}$ reaction even at incident energies larger than the Coulomb barrier [11].

In this work we present CDCC calculations for elastic scattering (including extracted total reaction cross sections), total fusion, and breakup of weakly bound stable (${}^6\text{Li}$ and ${}^7\text{Li}$) and radioactive (${}^6\text{He}$) light projectiles from a medium-mass target (${}^{59}\text{Co}$). As far as exotic halo projectiles are concerned, a systematic study of ${}^4,6\text{He}$ induced fusion reactions [7] with an improved three-body CDCC method [9, 10] using a dineutron model for ${}^6\text{He}$ (α - ${}^2\text{n}$) is in progress. Some preliminary results on total fusion of ${}^4\text{He}$ and ${}^6\text{He}$ with ${}^{59}\text{Co}$ will be presented for the first time in the last Section of the paper.

CDCC DESCRIPTION OF ${}^{6,7}\text{Li}+{}^{59}\text{Co}$ ELASTIC SCATTERINGS

In the present work, detailed CDCC calculations for the interaction of ${}^{6,7}\text{Li}$ on the medium-mass target ${}^{59}\text{Co}$ are applied in order to provide a simultaneous description of elastic scattering, fusion as well as breakup.

Details of the calculations concerning the breakup space (number of partial waves, resonances energies and widths, maximum continuum energy cutoff, potentials, ...) have been given in previous publications [9, 10] (in particular in Tables I, II and III of [10]). The CDCC scheme is available in the general coupled channels (CC) code FRESKO [12].

Before investigating whether the proposed CDCC formalism can be also applied to halo nuclei such as ${}^6\text{He}$, we present the full description of the ${}^6\text{Li} \rightarrow \alpha+d$ and ${}^7\text{Li} \rightarrow \alpha+t$ clusters as two-body objects, respectively. In the fusion calculations the imaginary parts of the off-diagonal couplings were neglected, while the diagonal couplings included imaginary parts [10]. Otherwise full continuum couplings have been taken into account so as to reproduce the elastic scattering data [7, 11]. We have used short-range imaginary fusion potentials for each fragment separately. This is equivalent to the use of incoming wave boundary conditions in CCFULL calculations [6].

Results of the comparison of the CDCC calculations for the elastic scattering with data of Ref. [7, 11] are shown in Fig. 1 for ${}^7\text{Li}+{}^{59}\text{Co}$ (left panel) and ${}^6\text{Li}+{}^{59}\text{Co}$ (right panel), respectively. The two different curves are the results of calculations performed with (solid lines) and without (dashed lines) ${}^{6,7}\text{Li} \rightarrow \alpha + d, t$ breakup couplings with the continuum (i.e. continuum couplings).

It is interesting to note that the initial optical-model analysis (OM) adopted by Souza and collaborators [11] was found to be ambiguous for the two lowest energies when using a parameter-free nonlocal potential. The agreement between the full calculations and data is very good. A similar comparison has been provided for the elastic scattering of both ${}^7\text{Li}+{}^{65}\text{Cu}$ and ${}^6\text{Li}+{}^{65}\text{Cu}$ reactions [13]. The effect of breakup on elastic scattering, stronger for ${}^6\text{Li}$ as expected, is illustrated by the difference between the one-channel calculations (comparable to the OM calculations [11]) and the full CDCC results.

The same CDCC description that uses potentials (similar to OM Potentials of [11]) to fit the measured elastic scattering angular distributions [7, 11] of Fig. 1 permits one to calculate total reaction cross sections (full curve) and non capture breakup (NCBU) yields, as defined in [1]) and plotted in Fig. 2 (curve labelled NCBU) with a comparison with the ${}^6\text{Li}+{}^{59}\text{Co}$ data of Ref. [14]. The effect of the ${}^6\text{Li}$ breakup and its competition with other reaction mechanisms is discussed more deeply in the following Section.

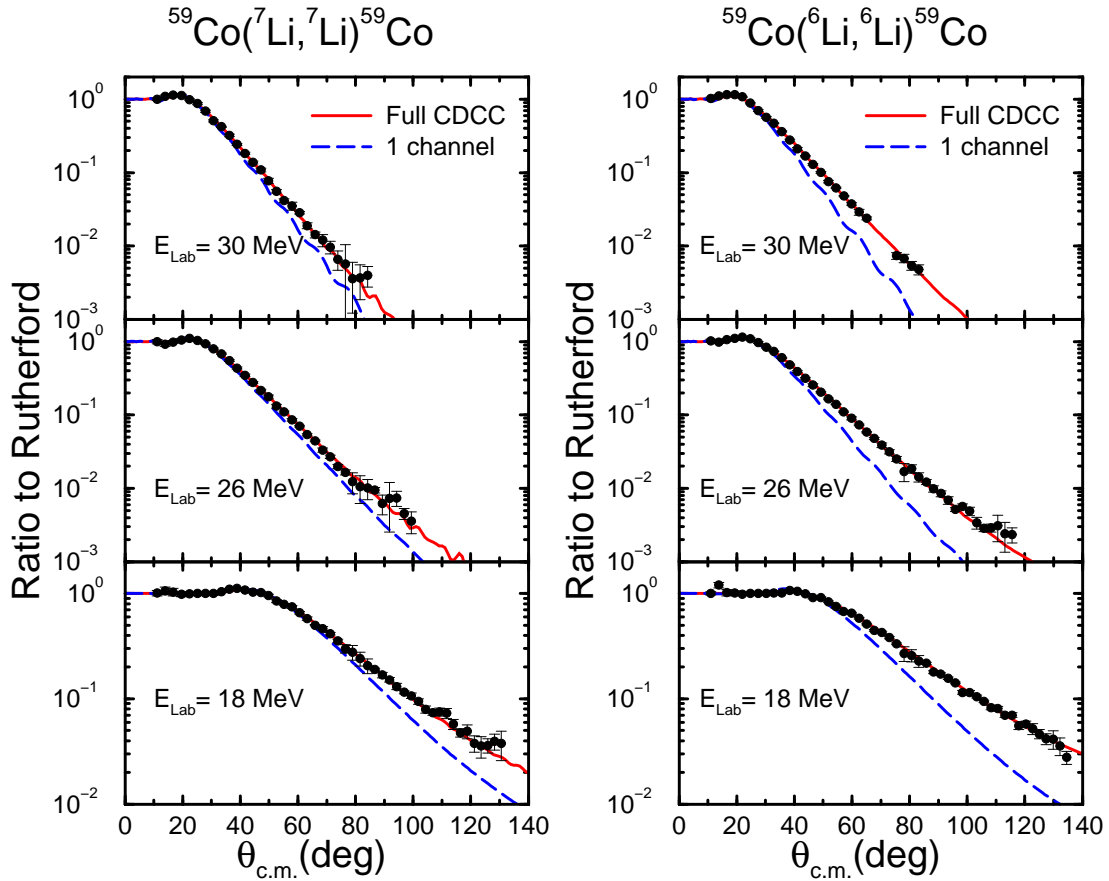


FIGURE 1. Elastic scattering for ${}^7\text{Li}+{}^{59}\text{Co}$ [7] (left panel) and ${}^6\text{Li}+{}^{59}\text{Co}$ [7] (right panel). The curves correspond to CDCC calculations with (solid lines) or without (dashed lines) couplings with the continuum as discussed in the text.

FULL CDCC DESCRIPTION OF BREAKUP FOR ${}^6\text{Li}+{}^{59}\text{CO}$

The total calculated breakup cross sections, plotted in Fig. 2 by the dashed-double-dotted curve labelled NCBU [14], were obtained by integrating contributions from the states in the continuum up to 8 MeV. They are found to be rather small compared with total fusion (TF) CDCC cross sections [10] (dotted line) or with complete fusion (CF) cross sections (dotted-dashed line) extrapolated from published TF data [6]. These large discrepancies have also been observed for the ${}^6\text{Li}+{}^{208}\text{Pb}$ reaction [8].

The total reaction cross sections obtained from fits with OM potentials [11] (dashed line with black points for ${}^6\text{Li}$ in Fig. 2 but not shown for ${}^7\text{Li}$) and CDCC calculations (solid line) are mostly dominated by TF cross sections. Their cross section ratios confirm the observed small enhancement of TF cross section for the more weakly bound ${}^6\text{Li}$ nucleus at sub-barrier energies [6]. Similar yields were measured for both reactions at and above the Coulomb barrier [6] in concordance with CDCC calculations [10] for both TF and total reaction cross sections.

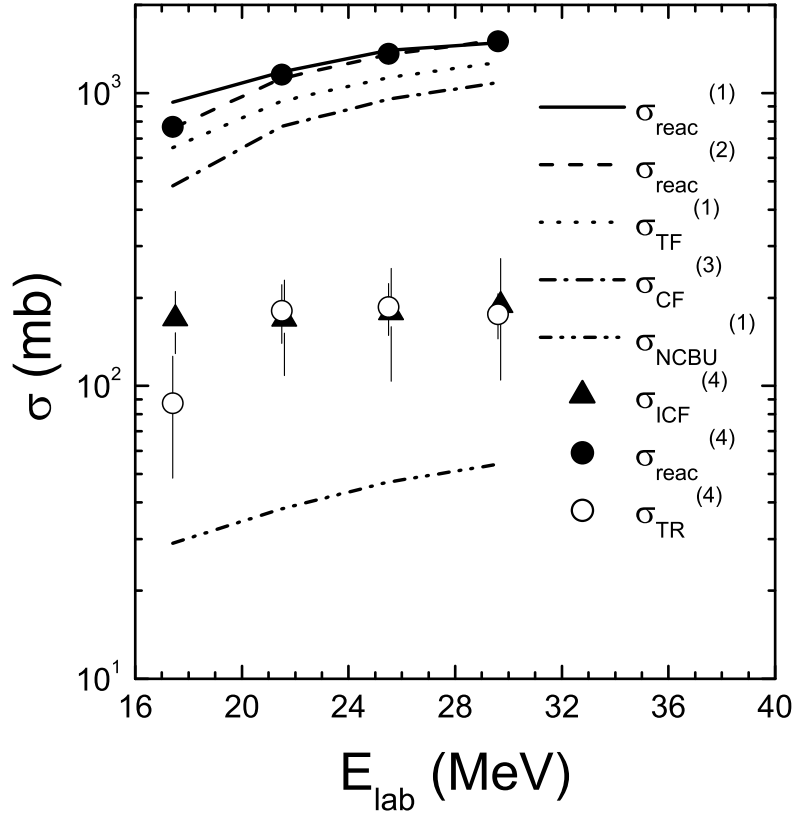


FIGURE 2. ${}^6\text{Li}+{}^{59}\text{Co}$ excitation functions evaluated with (1) CDCC (2) OM fits [11] (3) CF extrapolations and (4) TR data [14] and ICF = TF-CF [14].

Although the calculated values are significantly smaller than CF and other measured cross sections (incomplete fusion ICF and transfer TR) for all energies, the previous analysis of the ${}^6\text{Li}+{}^{59}\text{Co}$ reaction appears to be quite comprehensive when most of the cross sections are compared in a consistent way. However, it is still to be determined how much of TR yields are included in the so-called measured breakup cross section.

CDCC DESCRIPTION OF ${}^6\text{He}+{}^{59}\text{Co}$

In the following we present similar calculations applied to the two-neutron halo nucleus ${}^6\text{He}$. The present case is much more complicated since ${}^6\text{He}$ breaks into three fragments ($\alpha+n+n$) instead of two ($\alpha+d$), and the CDCC method is in current development for two-nucleon halo nuclei [15, 16]. Hence a dineutron model [17] is adopted for the ${}^6\text{He}+{}^{59}\text{Co}$ reaction: i.e. we assume a two-body cluster structure of ${}^6\text{He} = {}^4\text{He}+{}^2n$ with an α -particle core coupled to a single particle, a dineutron (2n). Couplings to resonant (2^+ , $E_{ex} = 0.826$ MeV) and non-resonant continuum states (up to f-waves) are included. The fact that the

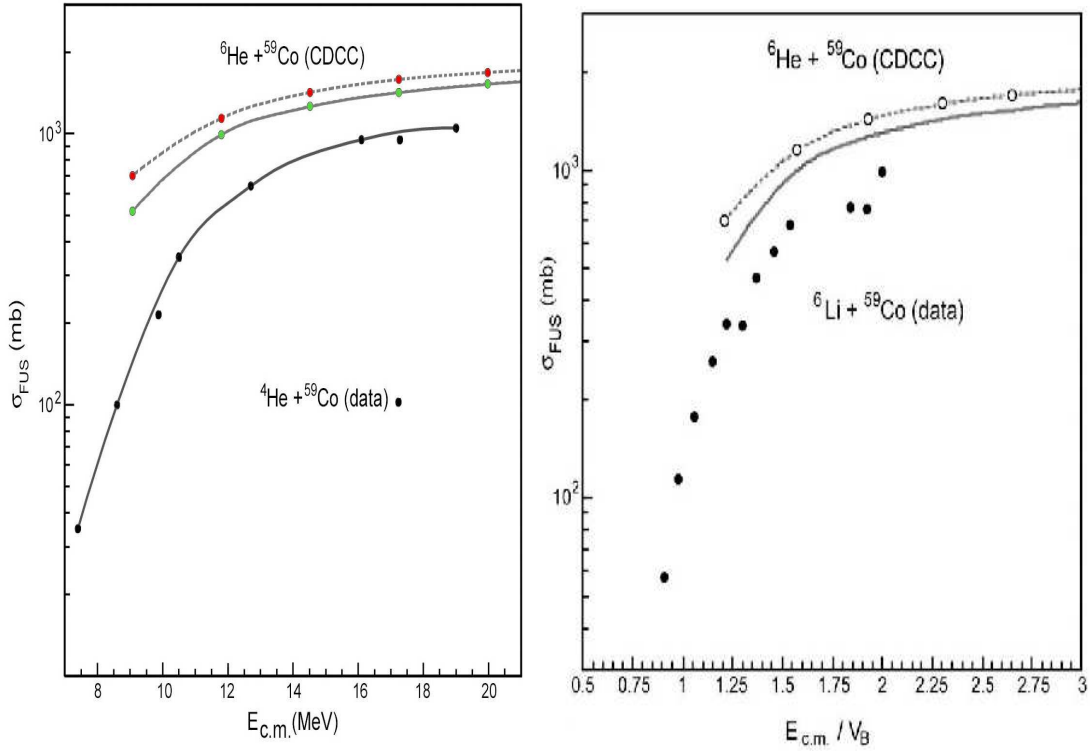


FIGURE 3. Total fusion excitation functions for ${}^4\text{He}+{}^{59}\text{Co}$ (data points [18] and solid black line for CC predictions on left panel) for ${}^6\text{Li}+{}^{59}\text{Co}$ (data points [6] on right panel), and for ${}^6\text{He}+{}^{59}\text{Co}$. The curves correspond to CDCC calculations for ${}^6\text{He}+{}^{59}\text{Co}$ with (dashed line) or without (thin line) couplings to the continuum.

dineutron is not an object with both fixed size and fixed energy (Heisenberg principle) might be a critical point in the present model.

Results of the CDCC calculations for TF of the ${}^6\text{He}+{}^{59}\text{Co}$ system compared to ${}^4\text{He}+{}^{59}\text{Co}$ and ${}^6\text{Li}+{}^{59}\text{Co}$ are shown in Fig. 3. On the left panel of Fig. 3 we compare the total fusion excitation functions of the ${}^6\text{He}+{}^{59}\text{Co}$ (CDCC calculations) and ${}^4\text{He}+{}^{59}\text{Co}$ (experimental data of Ref. [18]) reactions. The first calculation (solid line) only includes the reorientation couplings in fusion without breakup. All continuum and reorientation couplings are included in fusion with breakup (dashed curve). We observe that both calculated curves (with and without breakup) give much larger TF cross sections for ${}^6\text{He}$ compared to ${}^4\text{He}$. We also observe that the inclusion of the couplings to the breakup channels notably increases the TF cross section for all energies.

The same conclusions are reached when we compare on the right panel of Fig. 3 the TF excitation functions of the ${}^6\text{He}+{}^{59}\text{Co}$ (CDCC calculations) and ${}^6\text{Li}+{}^{59}\text{Co}$ (data points from [6], known to be well described by CDCC calculations [10]) reactions. For the ${}^6\text{He}$ reaction, the incident energy is also normalized with the Coulomb barrier V_B of the bare potential. Extended calculations are in progress to quantify the role of 1n- and 2n-transfer channels found to be significant in recent ${}^6\text{He}$ data [1, 3, 4, 5, 19, 20].

SUMMARY AND CONCLUSIONS

The CDCC method [9], already shown to be rather successful for fusion [10], can be used to provide the almost complete theoretical description of all competing processes (total fusion, elastic scattering, transfer and breakup) in a consistent way. In this paper we have shown that the ${}^6\text{Li}+{}^{59}\text{Co}$ reaction can be fairly well understood in this framework although CDCC does not separate CF from ICF. The question remains open for the halo nucleus ${}^6\text{He}$.

Some of the preliminary CDCC results for the ${}^6\text{He}+{}^{59}\text{Co}$ fusion process are presented here for the first time. The predictions for the ${}^{59}\text{Co}$ target are consistent with the data published for other medium-mass targets such as ${}^{64}\text{Zn}$ [19] and ${}^{63,65}\text{Cu}$ [20]. However a full understanding of the reaction dynamics involving couplings to the breakup and neutron-transfer channels will need high-intensity radioactive ion beams to permit measurements at deep sub-barrier energies and precise measurements of elastic scattering and yields leading to transfer channels and to the breakup itself. The application of four-body (required for an accurate α -n-n description of ${}^6\text{He}$) CDCC models under current development [15, 16] will then be highly desirable.

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